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SciVerse ScienceDirect
Procedia Engineering 47 (2012) 1133 – 1136
Procedia Engineering
www.elsevier.com/locate/procedia

Proc. Eurosensors XXVI, September 9-12, 2012, Kraków, Poland

Vertical integration technologies for optical transmissive 3-D microscanner based on glass microlenses

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Abstract

This paper describes crucial technological aspects of development of an optical, transmissive, vertically-integrated 3-D microscanner: chip-level bonding of micro-optical components and wafer-level anodic bonding of deeply structurized substrates. We present two methods of hybrid integration of glass microlenses with fragile movable parts of silicon microactuators, based on glass frit bonding or direct thermal bonding, that have been experimentally validated in terms of bonding strength, anodic bonding compatibility and change of optical performance of microlens. We also demonstrate the 3D stacking technology, based on sequential multi-level anodic bonding, successfully tested with deeply structurized silicon/glass wafers. Presented methods are of general importance for vertically integrated M(O)EMS Si/glass devices.

Keywords: MOEMS; optical microscanner; assembly technology; vertical integration; bonding; glass microlens

1. Introduction

Wafer-level vertical integration of heterogeneous building blocks (e.g. MEMS actuators, microlenses, opto-electronics) using appropriate bonding methods is an attractive way to build free-space micro-optical systems. This approach allows implementing of compact and possible array-type architectures with simplified optical path and possibility of on-wafer-packaging of sensitive M(O)EMS components. The authors demonstrated this approach in the development of micromachined confocal microscope [1] and more recently for array-type Mirau interferometer [2]. One of the main challenges concerns the multi-level bonding of functional wafers (up to 7 wafers) and compatibility of this bonding process with

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doi:10.1016/j.proeng.2012.09.351

integration method of micro-optical components (e.g. microlenses) in terms of bonding temperature, mechanical force etc.

This paper refers to the development of a vertically integrated optical 3-D microscanner, which is a key component for a number of scanning imaging microsystems, such as confocal microscopes on-chip or OCT probes for microendoscopy. The operation principle of the microscanner relies on steering of a collimated laser beam when it passes through two movable glass microlenses, integrated onto MEMS electrostatic Z-axis and X-Y-axis microactuators (Fig. 1). According to the vertical integration scheme, all components are batch fabricated on 4" silicon and glass wafers, aligned and bonded at wafer scale, providing at the same time hermetically sealed packaging for micro-optics. The scanning microlenses are hybrid integrated with microactuators, i.e. individually assembled onto microactuators and collectively bonded at wafer scale. Hence, the fabrication of the device requires developing of two compatible bonding processes: (1) chip-level bonding of glass microlens with movable platforms of two actuators, followed by (2) wafer-level bonding of several processed substrates.

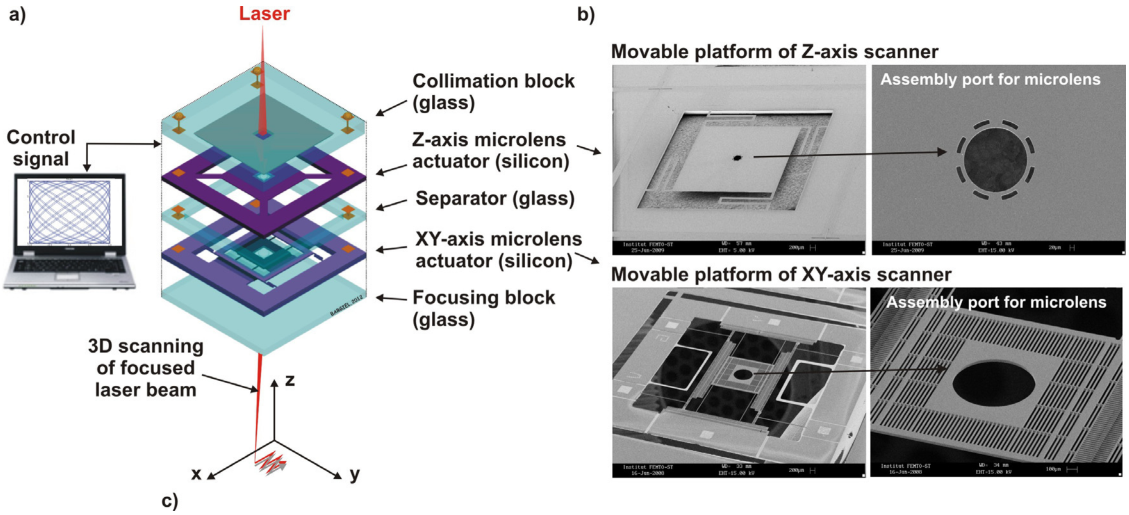

Fig. 1. Vertically integrated micromachined 3-D microscanner: a) expanded view of silicon and glass building blocks, b) details of silicon electrostatic scanners for displacement of scanning microlenses.

2. Chip-level bonding of glass microlenses

Chip-level bonding of glass microlens was tested by use of a single silicon chip with 15-µm-thick suspended platform ($4x4mm^2$) and commercial glass microspheres with diameter of 300µm±1µm (N-BK7 glass, Tg= 557°C, Edmund Optics). Microspheres were manually inserted into a assembly port (ϕ=295µm), formed by DRIE in the centre of the platform, and underwent two different procedures of thermal bonding: a direct thermal Si-Glass fusion at high temperature without any intermediate material or glass frit bonding at medium temperature with intermediate layer applied.

Direct bonding was carried out in an atmosphere furnace according to heating ramp with small initial heating rate (~2.7°C/min) to the process temperature at 650°C, gradually cooling through the annealing range (570-350°C), and natural cooling to the room temperature. Figure 2b presents 3D topography of the suspended platform without microlens and after thermal bonding of glass microlens. In the latter, a slight deformation (tilt) of the entire platform may be observed, more likely caused by the deformation of external frame of a chip. Light ring, which surrounds microlens and assembly port, clearly visible in the SEM picture (Fig. 2c), may indicate surface evaporation of specific components of glass.

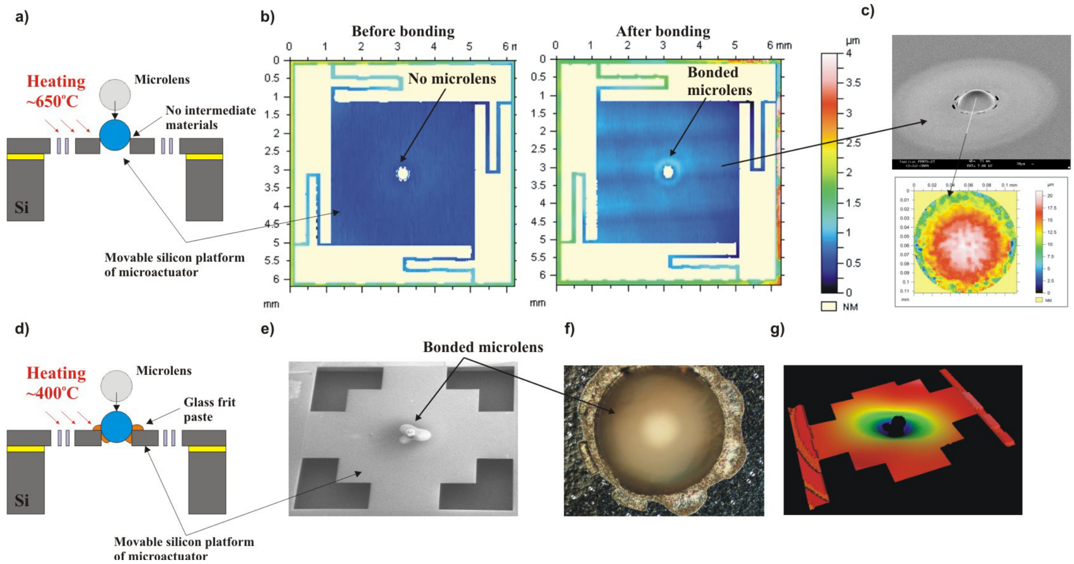

Fig. 2. Hybrid integration of glass ball microlens. 1. Direct Si-Glass bonding method: a) schematic view, b) 3D topography of suspended platform before and after microlens bonding, c) SEM and 3D topography of center part of the bonded microlens. 2. Glass frit bonding method: d) schematic view, e) SEM of platform with bonded microlens, f) back-side view of bonded microlens (optical microscope), g) deformation of thin silicon platform after bonding of microlens using glass frit material.

In case of glass frit bonding, the microlens was inserted into the assembly port and several small droplets of highly viscous glass frit paste (FX-11-0366, FERRO) were dispensed on the microlens-platform interface. Next, the organic binder in the paste was driven out by heating the paste at 120°C for 30min. After that, the paste was glazed at ~400^{o}C for 30 min to form reliable mechanical connection (Fig. 3ef). Optical inspection of the suspended structure using a white light interferometer has shown significant deformation of about 30µm, symmetrically localized around the assembly port (Fig. 2g).

Simple mechanical tests were carried out to verify the bonding robustness provided by both methods. Test structures have passed successfully intensive ultrasonic agitation in water and spin-rinsing. In addition, the silicon-glass bond, obtained by direct bonding, was forcefully broken and examined under microscope. Many breakage of silicon at the interface were found which suggests that direct bonding can have the bonding strength that is as strong as the fracture strength of silicon.

3. Wafer-level anodic bonding

To assemble the complex microscanner, a stack of 7 wafers have to be accurately bonded and aligned. The final system consists of 4 silicon wafers and 3 glass wafers. The silicon wafers are used to create active moving components in a SOI configuration to enable the scanning function of the device in x/y and z-direction. The glass wafers have at the same time passive optical function as well as they form the interface (electrically and optically) to the outside of the system. The SOI wafers have cavities in the handle layer for optical reasons. The cavities allow also the free movement of the actuators that are formed in the device layer. First the SOI wafers with the included cavity are made by silicon direct bonding. The other components are subsequently bonded by anodic bonding. Therefore the SOI wafers and glass wafers are placed alternating in a way that the there is always an interface consisting of glass and silicon [3].

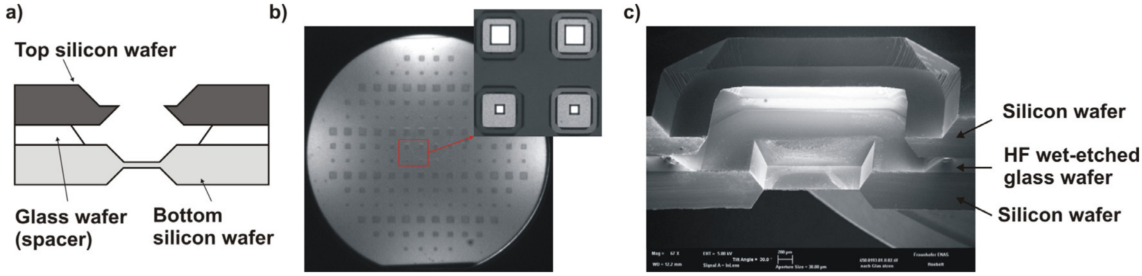

Fig. 3. Wafer-level anodic bonding for vertical integration of 3-D microscanner: a) schematic of Si-Glass-Si test sample, b) successfully bonded 4-inch wafers, c) cross-section of individual structure, showing high quality bonding at two Si-Glass interface.

The key point in this sequence is the correct electrical contact of the different wafers. A multiple stack of sequentially bonded silicon and glass wafers cannot by simply contacted from both outside surfaces because of the risk that sodium ions in the glass would diffuse in the already previously bonded interface and create reliability problems. Therefore an intelligent contacting scheme is necessary that either shortcuts such interfaces or allows contacting of selected wafers from the side. Using that technology it is possible to bond stacks of multiple wafers. (Fig. 4)

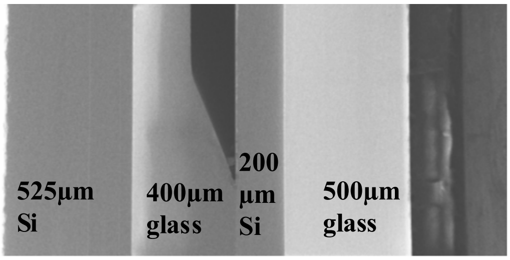

Fig. 4. SEM cross section of stack of 4 wafers (Si-glass-Si-glass) by anodic bonding.

4. Summary

We have presented two methods of hybrid integration of glass microlenses with fragile movable parts of silicon microactuator - direct thermal bonding and glass frit bonding. These methods are compatible with the 3D stacking technology, based on sequential multi-level anodic bonding, which was successfully tested with deeply structurized silicon/glass wafers. Presented technologies are investigated for micromachined 3-D microscanner but there are of general importance for different type vertically integrated M(O)EMS Si/glass devices.

Acknowledgements

The work was performed in the frame of DWST-DIS, founded by Project Inter Carnot-Fraunhofer (PICF)

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